Original Research

Sensitivity of Prescribing High-Intensity, Interval Training Using the Critical Power Concept

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ABSTRACT

International Journal of Exercise Science 8(3): 202-212, 2015. The critical power (*CP*) concept enables the calculation of time to exhaustion (t_{LIM}) for a given power output above *CP* using the equation of $t_{LIM} = W'/(\text{power} - CP)$, where *W′* is the curvature constant, and *CP* is the asymptote for the power-t_{LIM} relationship. The *CP* concept offers great promise for prescribing high-intensity interval training (HIIT); however, knowledge on the concept's sensitivity is lacking (i.e., how much of a difference in *W′* expenditure is needed to evoke different metabolic responses). We tested if two different power-t_{LIM} configurations expending identical proportions of *W′* would evoke different end-exercise oxygen uptake (VO_2) and heart rate (HR) values. Five men and five women completed a graded exercise test, 3-min all-out exercise tests, and intervals prescribed to deplete either 70 or 80% of *W′* on separate visits. Consistency statistics of intraclass correlation (ICC α), standard error of measure (SEM), and coefficient of variation (CV) were calculated on end-exercise values. End-exercise VO_2 were similar for the 3.5- and 5-min bouts, depleting 70% of *W′* (ICC α = 0.91, SEM = 3.23 mL·kg^{-1}·min^{-1}, CV = 8.1%) and similar for the 4- and 5-min bouts, depleting 80% of *W′* (ICC α = 0.95, SEM = 2.34 mL·kg^{-1}·min^{-1}, CV = 8.1%). No VO_2 differences were observed between trials or conditions ($p = 0.58$). Similarly, HR values (~181 b·min^{-1}) did not differ between trials or conditions ($p = 0.45$). Use of the CP concept for HIIT prescriptions of different power-t_{LIM} configurations evokes similar end-exercise VO_2 values on a given day. Our findings indicate that >10% *W′* depletion is necessary to evoke different metabolic responses to HIIT.

KEY WORDS: Anaerobic capacity, critical speed, fatigue, oxygen uptake

INTRODUCTION

High-intensity, interval training (HIIT) involves engaging in a series of high-intensity exercise bouts, interspersed with recovery, for the purpose of training both the aerobic and anaerobic energy systems (30). Indeed, HIIT in comparison to moderate-intensity, steady-state exercise evokes gains in maximum oxygen uptake (VO_{2max}) more rapidly (4). Moreover, when compared with moderate exercise, HIIT imparts better improvements in heart rate variability (23), endothelial function (23, 31, 36), and insulin sensitivity (31). Thus, an ability to prescribe HIIT with clinical populations has gained popularity.

Cardio-metabolic responses to HIIT are dependent on the exercise intensity domain. Interval bouts conducted above the gas exchange threshold (GET), within the heavy exercise domain, evoke an oxygen uptake (VO_2) slow component which is attenuated in subsequent bouts (32); however, delayed steady-states in cardio-metabolic responses are achieved (7). Conversely, exercise above the critical power (*CP*) for cycling or critical speed (*CS*) for running, within the severe exercise domain, evoke non-steady state responses (7). Specifically, VO_2 rises in time-dependent toward VO_{2max}, and does so more rapidly the higher the intensity is relative to *CP* (18).

Several groups have reported favorable short-term benefits of HIIT using bouts consisting of 30 s, all-out bursts interspersed with recovery (15). Such HIIT regimes require the subjects to self-pace their effort. Conversely, the *CP* or *CS* concept can be used to provide a specific time for a given power or running speed for prescribing HIIT (22). The method requires determining two parameters: 1) *CP*, a parameter representing the mechanical equivalent of the maximal lactate or VO_2 steady state; and 2) *W′* (pronounced W-prime), a mechanical measure of the finite work capacity above *CP* (N.B., the *D′* notation is used to represent the maximal displacement capacity above *CS* when referring to running or swimming) (20). Once the two parameters of *CP* and *W′* are established, partial expenditures of *W′* can be derived to develop interval time limit prescriptions associated with specific power outputs exceeding *CP*. Thus, in comparison to 30 s all-out HIIT bouts, the *CP* concept provides a prescription that takes into consideration a subject's aerobic and anaerobic capacities.

Research involving the use of the *CP* concept in prescribing HIIT is scarce. Explanation for the underutilization of the *CP* concept for HIIT prescription may be attributed to the sole, prohibitive-nature of how *CP* and *W′* were determined. Traditionally, *CP* and *W′* were determined via linear regression of the slope and *y*-intercept, respectively, from the total work and time to exhaustion data from three or more exhaustive bouts (16). Vanhatalo et al. (34) introduced procedure whereby *CP* and *W′* could be derived from a 3-min all-out exercise test (3 MT), and subsequent investigators of developed 3 MT protocols that can be performed in a single visit (3, 8, 10, 24). Similarly in running, the 3 MT can be performed in a single visit (5, 26). Thus, the *CP* concept is easier to implement for HIIT prescriptions.

We recently evaluated the long-term training responses to two different HIIT regiments using the *CP* concept (9). In that study, we determined 3 intervals were permitted with prescriptions depleting 80% of *W′*, whereas 4 intervals were permitted with prescriptions depleting 60% of *W′*. Such observations were true regardless of whether the intervals were shorter or longer in duration (i.e., 3 to 5 min). We also had a few days where subjects completed 3 intervals depleting 70% of *W′*; however, the end-heart rate responses in comparison to the 60 and 80% trials varied (unpublished observations). Such an observation prompted us to question the sensitivity of

W′ for prescribing HIIT using the *CP* concept.

In the present study, we tested the efficacy of the *CP* concept to prescribe two interval bouts of two different power-time limit (t_{LIM}) configurations depleting identical proportions of *W′*. Variability of the end-exercise VO_2 and heart rate (HR) values were examined. We examined two power-t_{LIM} configurations depleting 70% and 80% of *W′*, respectively. Our hypothesis was that similar end-exercise values would be observed on the same day for the given percentage *W′* depletion regardless of power-t_{LIM} configuration. Our second hypothesis was that end-exercise VO_2 and HR values would differ between the selected proportions of the 70 and 80% *W′* depletion conditions; thus suggesting the sensitivity of the *CP* interval prescription was within 10%.

METHODS

Participants

Ten subjects completed a graded exercise test (GXT) and 3 MT (6, 34) for determination of *CP* and *W′*. The subjects then returned for two separate visits to complete two HIIT regimes. Each regime involved intervals prescribed to deplete specific proportions of *W′* using either a higher power output, shorter time scheme or a lower power, longer time scheme. Heart rate and VO_2 were monitored for each interval, and the end-exercise values were used for statistical evaluation.

Five men and five women (age = 21 ± 2 yr, height 171 ± 7 cm, body mass 70 ± 8 kg) were recruited to participate in our study. Informed consent, health history, and institutional review board approval were obtained prior to data collection. The subjects confirmed verbally their compliance to the directions to avoid strenuous exercise and the consumption of alcohol 24 hr prior to each visit. The subjects also confirmed verbally their avoidance of consuming caffeine-containing products the day of testing.

Protocol

Each subject completed a cycle ergometry GXT with a square-wave verification bout to establish maximum oxygen uptake (VO_{2max}). The second and third visits were scheduled for the 3 MT. The first of two visits was for the purpose of familiarization, and the second visit was to establish *CP* and *W′* (*Eqn. 3*). The subjects then returned to the laboratory for two separate visits to perform a sequence of shorter and longer interval bouts, established using the *CP* concept, to expend either 70% or 80% of *W′*. Both the interval times (i.e., shorter vs. longer) and intensities (i.e., 70% and 80%) were counterbalanced to avoid order-effects. All trials were completed on the same electronically braked cycle ergometer (Lode Excalibur Sport, Groningen, The Netherlands) with the seat and handlebar settings recorded, and the preferred cadence standardized for each trial (i.e., the rpm selected for the GXT). Heart rate (Polar Instruments, Oulu, Finland) and VO_2 values (Parvomedics TrueOne, Sandy, UT) were recorded breath-by-breath and reported at 4 samples per min (i.e., 15 s averaging). The system was calibrated prior to each subject's visit according to the manufacturer's instructions.

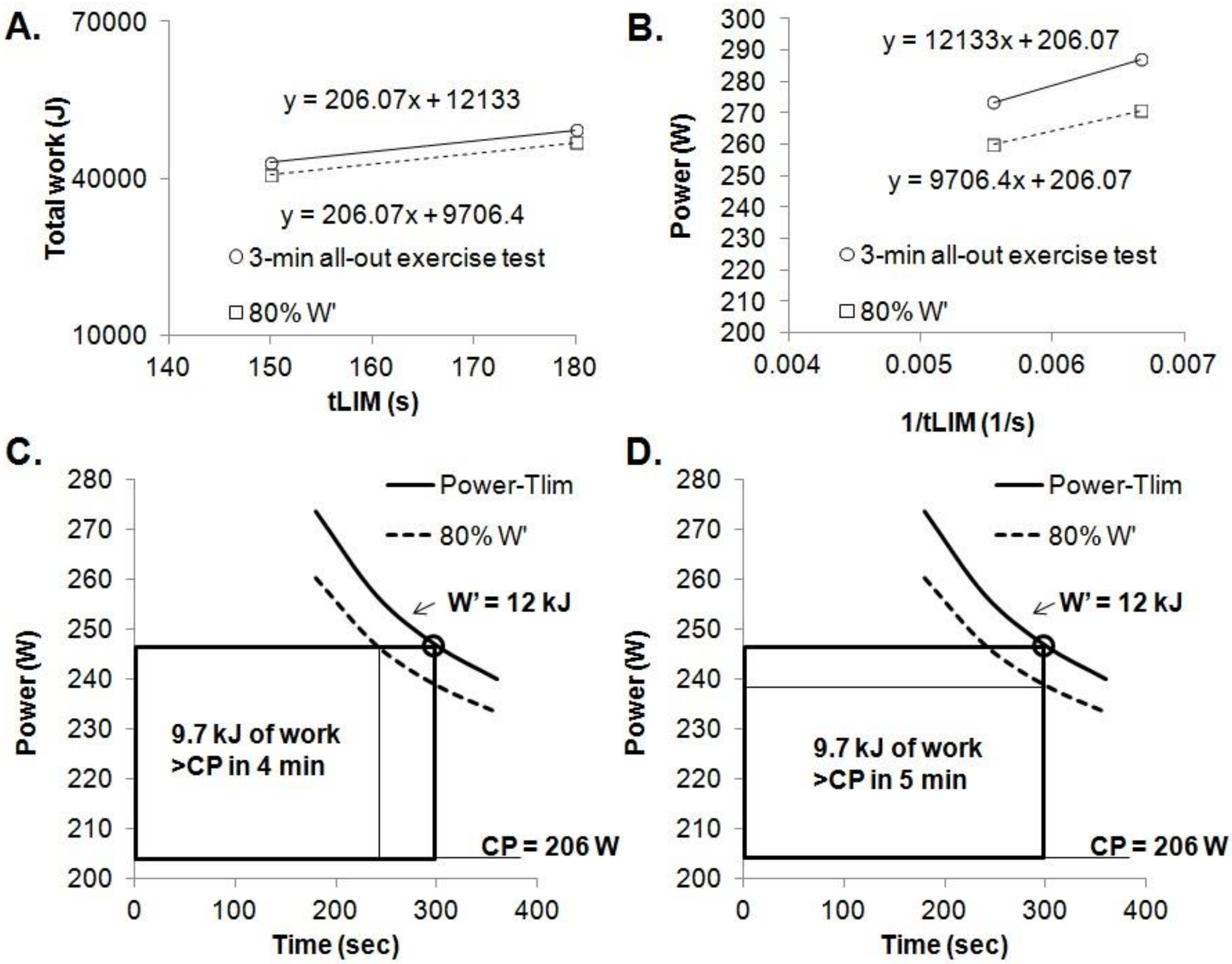

Figure 1. Sample illustration of interval prescriptions based off the 3-min all-out exercise test for a representative subject. Work at 150 and 180 s (Panel A) reveals *CP* (206.07 W) and *W′* (12133 J), which is corroborated by power and the inverse of t_{LIM} (Panel B). Panel C denotes a prescription where power corresponding to t_{LIM} of 5 min is maintained, but time is reduced by 0.80. Panel D denotes a prescription where the time of 5 min is maintained and power relative to *CP* is reduced proportionately by 0.80. The same method of prescription was used for the 70% interval bouts.

The custom cycling GXT was derived based on the subject's body mass index, age, sex, and physical activity level, along with an estimate for the power evoking VO_{2max} (P_{peak}) (25). A target GXT duration of 10 min was selected (21), and the intensity for the exhaustive, verification bout was set at end-GXT power minus two stages given to enable a longer period of time to ensure a plateau in VO_2 (29). Exhaustion was defined by a decline in 10 rpm below preferred cadence for more than 10 sec. Retesting was performed if the highest VO_2 values between the GXT and verification bout differed more than 3% (N.B., retesting was necessary for one subject) (21). GET from the GXT was estimated using the V-slope method (2). To calculate the power evoking GET (P_{GET}), we presumed there was a 1-min delay of gas-exchange response to a given power output (8).

The components of CP and W' were determined using the 3 MT (34). In brief, the linear factor for the load was derived by 50% of the difference of P_{GET} and P_{peak} (50% Δ) divided by the preferred cadence squared (W/rpm^2). Data were exported from the ergometer at 6 Hz, and power relative to time data were Butterworth-filtered to derive CP (last 30 s). The W' parameter was determined using 150 s (P_{150s} – CP), where P_{150s} is the power during the initial 150 s (19).

On separate days, subjects completed shorter and longer interval bouts predicted to deplete either 70% or 80% of W′, with 15-min rest between bouts. Prior investigators (12) have reported that if an interval depletes W' wholly, 15 min is sufficient to restore W′ up to 80%. For the shorter intervals, power was maintained, and time was reduced to 3.5 min or 4 min from the predicted t_{LIM} of 5 min for the 70% and 80% intensities, respectively. For the 5-min interval bouts, time was maintained, whereas power was reduced from the associated t_{LIM}. Equations for deriving interval times (T_i) or power ($Power_i$) were:

$$T_i = 1/[(P_{300s} - CP)/(0.80 \times W')], \text{ or } T_i = t_{LIM} \times 0.80 \quad (1)$$

and

$$Power_i = [(0.80 \times W')/300 \text{ s}] + CP, \quad (2)$$

where P_{300s} is the power corresponding to the 300 s t_{LIM} and 0.80 is the ratio expenditure of W'. When 70% depletion was prescribed, 0.80 was replaced with 0.70. The mathematics for the interval prescriptions of a representative subject are shown in Figure 1.

Statistical Analysis

End-exercise VO_2 and HR values for each bout were evaluated using an analysis of variance, and $p < 0.05$ was set as the limit for rejecting the null hypothesis. Intraclass correlation coefficients (ICC α), standard error of measurement (SEM), and coefficient variation (CV%) were calculated to evaluate the consistency of measurements. Summary statistics are reported as mean ± SD.

RESULTS

The highest VO_2 values for the GXT (48.2 ± 9.3 mL·kg^{-1}·min^{-1}) and the exhaustive, square-wave, verification bout (48.9 ± 9.3 mL·kg^{-1}·min^{-1}) were highly consistent (ICC α = 0.99, SEM = 1.12 mL·kg^{-1}·min^{-1}, CV= 1.7%), denoting the measurement of VO_{2max} was obtained. Power outputs evoking GET and 50% Δ from the GXT were 160.0 ± 48.1 W and 210.9 ± 50.9 W, respectively. The CP and W' values from the 3 MT were 202.3 ± 52.6 W and 8549 ± 7349 J, respectively.

The mean VO_2 by time-course plots for the 70 and 80% depletion of W' intervals are presented in Figure 2. No significant differences were observed for either the absolute ($F = 1.67$, $p = 0.26$) or relative ($F = 0.70$, $p = 0.58$) end-exercise VO_2 measurements between trial times or interval intensities. End-exercise VO_2 values were ~93 to 95% of VO_{2max}.

We found no significant differences in the end-exercise HR values ($F = 1.37$, $p = 0.45$) between trial times or interval intensities. The time-dependent gain in HR was similar

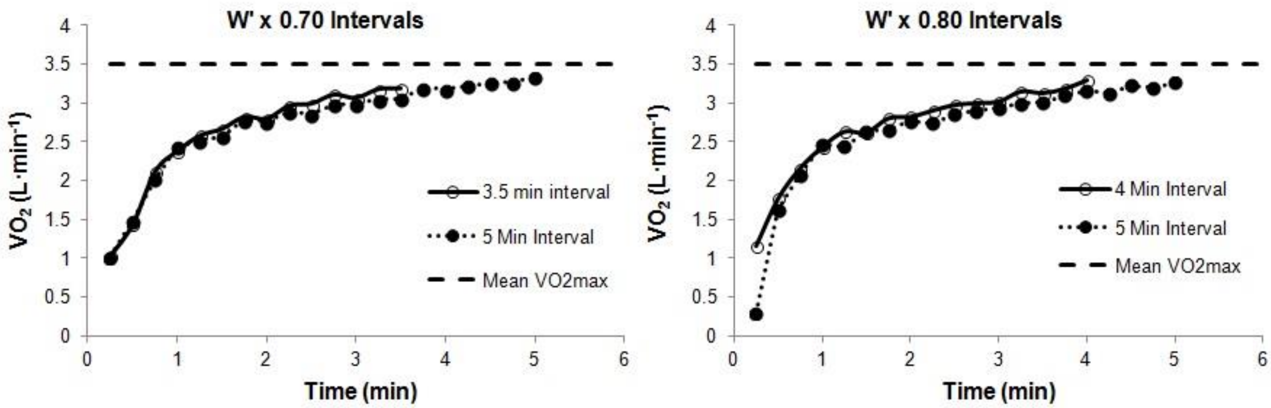

Figure 2. Mean VO_2-time plots for intervals depleting 70% (left) and 80% (right) of *W′* (N.B., error bars not shown for clarity). Take notice of different rates of rise for VO_2 yet similar end-VO_2 values for each interval.

to the pattern observed with VO_2 (Figure 2). As shown in Table 1, the end-exercise VO_2 and HR values were similar between the trials and interval intensities.

DISCUSSION

An overview of the primary findings for this study is as follows. Firstly, when intervals are prescribed by both maintaining power and reducing t_{LIM}, or by maintaining t_{LIM} and reducing power, similar end-exercise VO_2 values are evoked. These findings support the hypothesis that net gains in VO_2 during exercise above *CP* correspond with similar depletions of *W′*. Secondly, and in contrast to our second hypothesis, intervals prescribed to deplete 70 and 80% of *W′* did not evoke different end-exercising VO_2 values between conditions. Such a finding would indicate the sensitivity of *W′* to evoke different metabolic responses exceeds 10%.

As indicative of the VO_2 by time-course plots (Figure 2), VO_2 did not achieve a delayed steady-state, a result indicating that all intervals were prescribed within the severe exercise domain (i.e., >*CP*) (28). Presuming 15 min is sufficient to recover 80% of *W′*, if a prior interval wholly depleted *W′* (12), 15 min of recovery would hypothetically be sufficient to wholly replenish 70 to 80% of *W′* as well. Indeed, on a given day, the end-VO_2 values for the two power-t_{LIM} trials were similar based on the consistency statistics (Table 1).

The VO_2 by time-course plots also revealed an expected trajectory of VO_2 toward maximum. The *bona fide* characteristic of an exhaustive bout in the severe exercise domain is the attainment of VO_{2max} occurring at or just slightly prior to complete expenditure of *W′* (7). Our VO_2 by time-course records support the use of interval prescription using the *CP* concept to evoke predictable end VO_2 values (Figure 2). The rate of rise in VO_2 corroborated the expected depletion of *W′*. For instance, in the two power- t_{LIM} configurations prescribed to deplete 80% of *W′* (Figure 2, right panel), full depletion of *W′* for the 4-min trial would have corresponded to a t_{LIM} of 5 min. Based on

Table 1. Consistency of end-exercise oxygen uptake (VO_2) and heart rate values (see Figure 2 for VO_2-time responses).

		Mean ± SD		Consistency Statistics		
		3.5 min trial	**5 min trial**	**ICC α**	**SEM**	**CV**
70% of W′ Intervals	Absolute VO_2	3.18 ± 0.91 $L \cdot min^{-1}$	3.30 ± 1.00 $L \cdot min^{-1}$	0.93	0.25 $L \cdot min^{-1}$	8.2%
	Relative VO_2	45.4 ± 10.6 $mL \cdot kg^{-1} \cdot min^{-1}$	46.9 ± 11.6 $mL \cdot kg^{-1} \cdot min^{-1}$	0.91	3.23 $mL \cdot kg^{-1} \cdot min^{-1}$	8.1%
	Heart Rate	181.6 ± 8.3 $b \cdot min^{-1}$	182.0 ± 6.8 $b \cdot min^{-1}$	0.75	3.8 $b \cdot min^{-1}$	2.2%
		4 min trial	**5 min trial**	**ICC α**	**SEM**	**CV%**
80% of W′ Intervals	Absolute VO_2	3.23 ± 0.89 $L \cdot min^{-1}$	3.20 ± 0.90 $L \cdot min^{-1}$	0.96	0.18 $L \cdot min^{-1}$	5.8%
	Relative VO_2	45.6 ± 9.93 $mL \cdot kg^{-1} \cdot min^{-1}$	45.6 ± 10.2 $mL \cdot kg^{-1} \cdot min^{-1}$	0.95	2.34 $mL \cdot kg^{-1} \cdot min^{-1}$	8.1%
	Heart Rate	180.2 ± 9.6 $b \cdot min^{-1}$	181.8 ± 7.3 $b \cdot min^{-1}$	0.90	3.1 $b \cdot min^{-1}$	1.8%

the mean slope of rise in VO_2 between the third and fourth minute of the 4-min interval (i.e., a gain of ~0.25 $L \cdot min^{-1}$), attainment of VO_{2max} would have occurred in close proximity to 5 min. Similarly, when examining the gain between the fourth and fifth minute of the 5-min interval (0.20 $L \cdot min^{-1}$), t_{LIM} would have been projected to occur at ~7.5 min, with attainment of VO_{2max} occurring at or slightly prior to the t_{LIM} of 7.5 min.

The end-exercise VO_2 values for the intervals prescribed to deplete 70% of *W′* were not different from those of the 80%-depletion trials. Several plausible reasons may explain this non-difference. Firstly, the range of *W′* values amongst our sample was high, with the standard deviation for *W′* being nearly equivalent to the mean. Thus, in many cases, the power differences for the 70%- and 80%-interval training prescriptions may not have been substantial enough to detect significant differences in end-exercising VO_2. Secondly, we may have lacked sufficient statistical power to observe differences in end-exercise VO_2. Thirdly, the measure of *W′* may fluctuate from day to day (i.e., the parameter may have moderate reliability). Such a characteristic of *W′* would have an effect on the sensitivity to prescribe HIIT with the *CP* concept.

The *W′* represents the finite amount of work supported above the *CP*, a measurement attributed largely to a person's anaerobic-energy capacity. Debate on the reliability of anaerobic capacity appeared in the literature subsequent to the development of the maximally accumulated oxygen deficit (MOAD) method. The MOAD measure, determined from an exhaustive-exercise bout, was observed to fluctuate on a trial-retrial basis (11); yet, measurement of MOAD is a valid metric for anaerobic capacity on a given day (1). Hill et al. (17) conducted four separate trials of the MAOD metric and reported a 19% standard error of estimate.

In short, research on a MOAD would support the notion that the sensitivity of the anaerobic capacity, and by extension, *W′* exceeds 10%.

Few studies have investigated the reliability of *W′*. Gaesser and Wilson (14) conducted repeated exhaustive trials whereby *W′* was estimated using the linear power-inverse time model. The authors reported a moderate R^2 value of 0.62 for *W′*. Using their published raw data, we derived that their SEM for W′ was 1.5 kJ, and their CV was 10%. Johnson et al. (19) reported a SEM and CV for *W′* derived from two trials of the 3 MT were 1.5 kJ and 21%, respectively. Vanhatalo et al. (33) reported on a training study in which both the 3 MT and exhaustive trials were gathered at pre and posttraining. In response to training, the authors observed *W′* measured by the 3 MT increased by 0.6 kJ, whereas *W′* measured by exhaustive bouts decreased by 2.0 kJ. When interpreting these results one must keep in mind the t_{LIM} for exhaustion can vary day to day, which may explain some of the observed variability (35). Finally, Clark et al. (9) reported that *D′* for a group of 16 soccer players was moderately correlated (r = 0.62) from pre to posttesting. Both of these training studies indicate that use of the *W′* or *D′* to detect training effects is difficult because of the reliability of these metrics is not strong.

The collection of studies on anaerobic capacity, either measured by MOAD or the *W′* parameter, would suggest that the variability of the anaerobic capacity from day to day exceeds 10%. Thus, when applying *CP* concept to the prescription of HIIT, the sensitivity of *W′* should be kept in mind. For example, if *W′* is presumed to fluctuate more than 10%, an interval bout set to deplete 90% of *W′* may actually deplete 100% of the available *W′*, on a given day, causing attainment in VO_{2max} in only one interval. We tested the difference between 70 and 80% depletion of *W′* and failed to observe significant differences between the end-exercise VO_2 values. A more likely prescription for evoking different metabolic responses within the severe domain would be those 20% apart. For example, in a recent training study, we observed that subjects consistently performed 4 intervals depleting 60% of *D′* in running, and on a separate day, completed 3 intervals depleting 80% of *D′*. Establishing prescriptions by 10% or less between days (e.g., 60 or 70% intervals vs. 70 to 80% intervals) would appear to violate the sensitivity of the *CP* concept with respect to the variability of *W′*.

Strong evidence exists to suggest that the capacity for the number of intervals permitted on a given day is hyperbolically dependent upon the power-t_{LIM} relationship. For instance, Fukuda et al. (13) evaluated subjects completing 15 s of running intervals interspersed with 15 s of passive recovery, on separate days, at intensities of 110, 120, and 130% of the velocity evoking VO_{2max} determined from a GXT. The average number of trials that were completed declined in hyperbolic fashion relative to intensity (i.e., 27, 13, and 8 repetitions completed at 110, 120, 130%, respectively). Our data indicate that the total number of repetitions may vary with *W′* from day to day; however, the preservation of the hyperbolic nature for the capacity of the number of intervals relative to intensity would remain the same.

Based on our results, it is conceivable that end-exercise HR for an initial bout may be used to judge the variability of *W′* on a given day, and may differentiate variation of responses to intervals between days. Although estimates of VO_2 from HR have been reported to decline at higher intensities, if differences in the reserve below and above GET are taken into account, HR-derived estimates of VO_2 are very accurate, including when repetitive intervals are performed (27). In the present study, end-exercise HRs were consistent for the 70% versus the 80% bouts (Table 1).
We acknowledge our results are confined to cycle ergometry. Hypothetically, the *CP* concept also could be used to prescribe proportional intervals for running, swimming, rowing, etc. (20). With running, however, there is complexity in adjusting for differences in treadmill versus overground running along with extrapolation of grade with differences in treadmill speed (26). Additionally, factors such as wind resistance may create limitations to the model.

The results from the present study demonstrate that *CP* and *W′*, as estimated from a 3 MT (6, 34), can be used to prescribe intervals of different Power-t_{LIM} configurations to evoke similar end-exercise VO_2 values. Selection of 70% and 80% depletion of *W′* was insufficient to evoke different end-exercise VO_2 values. Instead, to evoke different metabolic responses, we recommend the difference in depleting *W′* exceed 10% (e.g., 60 and 80% of *W′*), but we recognize that using a lower percentage would enable the completion of more interval bouts.

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